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Hydrogeological experience in the use of MRS

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ABSTRACT

Nowadays, MRS contribution to characterize aquifers in common conditions down to about 100 meters deep is highly valuable in rocks that exhibit hydraulic behaviour of non-consolidated aquifer at the sounding scale (e.g. sediments, weathered and fissured hard-rocks, densely fissured or highly interstitial porous carbonates). In rocks that exhibit behaviour of fractured aquifer (e.g. low density fractured crystalline basements and limestone, karsts) MRS is a useful complementary method but is not always effective for common engineering studies. In magnetic rocks MRS measurements are often impossible. On the one hand, field experiences reveal that MRS is useful to characterize aquifers. (1) The geometry of saturated aquifer can be estimated in 1D case. Interpolation in-between 1D soundings also reveals 2D geometry if the size of MRS loops is smaller than about half the heterogeneity size. (2) Links between MRS water content and aquifer total porosity and storativity have been found. (3) The transmissivity is accurately estimated from MRS parameters in several geological contexts, using the appropriate conversion equation. (4) Thanks to the integrative property of the sounding, the spatial scale of measurement is considered by hydrogeologists as appropriate for aquifer characterization and modelling. (5) The aquifer characterization is improved when MRS is used in the framework of a hydrogeological methodology and jointly with complementary geophysical methods. On the other hand, field experiences reveal the main limitations encountered in the use of MRS with the actual instrumentation. (1) MRS is not yet self-sufficient to characterize aquifers as the MRS output parameters still need to be compared to hydrogeological properties to achieve quantitative estimation of transmissivity. Storage related parameters are not yet quantitatively accessible from MRS. (2) The electromagnetic noise lowers the signal to noise ratio and makes urban areas but also low interstitial porosity and poorly fractured rocks difficult to survey. (3) Heterogeneity of the magnetic properties of rocks makes measurements impossible or interpretations wrong. (4) Electrically conductive layers reduce the investigation depth of MRS in salty water and clayey environments.

Key words: geometry, hydrogeophysics, MRS, storativity, transmissivity

Experiencia en la utilización de los SRM en Hidrogeología

RESUMEN

Actualmente, la contribución que supone el uso de los SRM para la caracterización de acuíferos hasta los 100 m de profundidad, en condiciones normales, es de un gran valor en acuíferos con comportamiento hidráulico (a la escala del volumen involucrado en el SRM) de rocas no consolidadas (p.e. rocas sedimentarias, zona meteorizada, rocas fracturadas, rocas carbonatadas con un alto grado de fisuras o con gran porosidad intersticial). En rocas que presentan un comportamiento de acuíferos fracturados (p.e. basamento cristalino y calizas con bajo grado de fracturas, y en karst) el SRM es un método complementario de utilidad, pero no siempre efectivo en los estudios ordinarios. En rocas magnéticas no es posible, en general, la utilización de los SRM. Por una parte, las experiencias de campo demuestran que el uso de los SRM es de utilidad en la caracterización de acuíferos: (1) Puede estimarse la geometría de acuíferos saturados en el caso de 1D. La interpolación entre mediciones 1D permite también deducir la geometría en 2D si el tamaño de la antena utilizada en el SRM es más pequeño que aproximadamente la mitad de las dimensiones de la estructura. (2) Se ha demostrado que hay una relación entre el contenido en agua deducido por SRM con la porosidad total y con el coeficiente de almacenamiento. (3) A partir de los datos de un SRM, pueden hacerse estimaciones rigurosas de la transmisividad en varios contextos geológicos, mediante la utilización de las ecuaciones de conversión adecuadas. (4) Gracias a la propiedad integradora del método, el volumen de terreno involucrado en la medición es considerado por los hidrogeólogos como apropiado para la caracterización de acuíferos y su modelado. (5) La caracterización de acuíferos puede mejorarse cuando se utilizan los SRM en el contexto de una metodología hidrogeológica y junto con otros métodos geofísicos complementarios. Por otra parte, las experiencias de campo muestran las principales limitaciones en el uso de los SRM, con la instrumentación actual: (1) El método SRM no es todavía autosuficiente para la caracterización de acuíferos, ya que los datos obtenidos en un SRM necesitan ser comparados con datos obtenidos por métodos hidrogeológicos, para conseguir estimaciones cuantitativas de la transmisividad. Los valores cuantitativos del coeficiente de almacenamiento no son todavía obtenibles a partir de SRM. (2) La existencia de ruido electromagnético reduce la relación señal/ruido, por lo que en áreas urbanas, o en rocas con baja porosidad intersticial o de poco grado de fracturación, la medición resulta difícil. (3) La existencia de heterogeneidad en las propiedades magnéticas de las rocas da lugar a que las mediciones tampoco resulten posibles, o a que las interpretaciones resulten erróneas. (4) Las rocas eléctricamente conductoras reducen la profundidad de investigación de los SRM, como sucede en lugares con agua salada o con alto contenido en arcilla.

Palabras clave: almacenamiento, geometría, hidrogeofísica, MRS, transmisividad

Introduction

The main advantage of MRS as compared to other geophysical methods is that the measured signal is generated by groundwater molecules. The amplitude of the signal is proportional to the number of hydrogen nuclei of water molecules that generate the signal, and the decay of the signal is linked to the mean size of the pores that contain the hydrogen nuclei. After inversion of the measured signal, the main geophysical parameters obtained are the MRS water content θ_{MRS} and the decay constants T_2^* and T_1^* as functions of depth. The maximum investigation depth reached in common conditions with the actual instrumentation is about 100 meters. For the last ten years, several works assessed the links between output geophysical parameters, i.e. θ_{MRS}, T_2^* and T_1^*, and some of the hydrogeological properties of aquifers, i.e. the saturated aquifer geometry, storativity and hydraulic conductivity.

The first works conducted by geophysicists focussed on qualitative interpretation of the MRS parameters (among others Schirov *et al.,* 1991; Goldman *et al.,* 1994; Legchenko *et al.,* 1997). As field experiments proved the interest of MRS to hydrogeology, specific measurements were conducted to compare MRS parameters with hydrogeological properties of aquifers. MRS were implemented in the vicinity of boreholes where pumping tests were conducted, and conversion equations inspired by oil industry experiences were proposed to estimate the storativity and the transmissivity from MRS (among others Legchenko *et al.,* 2002; Vouillamoz, 2003; Vouillamoz *et al.,* 2007):

$$S_{c\_MRS} \approx S_{e\_MRS} = \rho g \Delta z(\alpha + \theta_{MRS}\beta) \approx C_e(\theta_{MRS}\Delta z) \quad [1]$$

$$S_{u\_MRS} \approx S_{y\_MRS} = C_y \theta_{MRS} \quad [2]$$

$$K_{MRS} = C_K(\theta_{MRS} T_1^{*2})$$

and

$$T_{MRS} = C_T(\theta_{MRS} T_1^{*2})\Delta z \quad [3]$$

where S_{c_MRS} and S_{e_MRS} are the MRS derived confined storativity and elastic storativity respectively, S_{u_MRS} and S_{y_MRS} are the MRS unconfined storativity and specific yield respectively, K_{MRS} and T_{MRS} are the MRS derived hydraulic conductivity and transmissivity respectively, Δz is the saturated thickness derived from MRS, ρ is the mass per unit volume of water, α and β, are the aquifer and water compressibility respectively, and C_e, C_y, C_K and C_T are parametric factors that are calculated comparing MRS estimators with hydrogeological properties (Table 1) as presented in Lubczynski and Roy (2007, this Issue). If the MRS decay constant T_1^* has not been measured, T_2^* can be used in a modified form of Equation 3 (Vouillamoz *et al.,* 2002):

$$K_{MRS} = C_K(\theta_{MRS}^4 T_2^{*2})$$

and

$$T_{MRS} = C_T(\theta_{MRS}^4 T_2^{*2})\Delta z \quad [4]$$

However, the conversion Equation 4 gave less accurate estimation of the transmissivity as compared to Equation 3 in several geological contexts (Vouillamoz, 2003) because T_2^* is more affected by heterogeneities of the magnetic Earth field.

Nowadays, hydrogeologists start to use jointly MRS with common hydrological tools to characterize saturated aquifers in a variety of geological contexts. This paper presents some of the valuable MRS field experiences conducted in the main hydrogeological contexts.

Case histories in non-consolidated sediments

Non-consolidated sediments are usually favourable contexts to the use of MRS because (1) the free water content of saturated sediments is high enough to achieve acceptable signal to noise ratio, and (2) the 1D assumption is often acceptable because of layered sedimentation. However, attention should be paid to the magnetic property of sediments that can make aquifer undetectable as observed by Roy *et al.* (2006) in coarse-grain sediments of South-east Canada (see section "Case histories in non-homogeneity magnetic Earth's field").

Saturated reservoir geometry

As MRS is nowadays sensitive to free water, it can measure in favourable conditions part of the capillary water in unsaturated zone and mobile water in saturated zone (Lubczynski and Roy, 2007 this Issue; Lubczynski and Roy, 2005). Consequently, the depth to saturated layer of unconfined aquifer can be accurately estimated only if the contrast of MRS parameters (water content and/or decay constants) between the unsaturated and the saturated reservoir is high enough. Medium sands to gravel are usually favourable if the clay content is low because capillary water of the unsaturated zone is almost negligible.

Vouillamoz *et al.* (2003) and Vouillamoz *et al.* (in press) compared the static water level (SWL) measured in wells with the MRS depth to saturated layer in several areas. They found an average difference *d* of -26%<d<+13% (population of 25, Figure 1A) and they concluded that MRS is useful in preliminary surveys to roughly estimate the SWL of unconfined aquifers. However MRS can not replace monitoring well because the uncertainty on MRS depth is high and increases with depth as compared to the uncertainty on SWL measurement (Figure 1B). As MRS estimates the depth to saturated layer, it can not estimate the SWL of confined aquifers.

Using the actual instrumentation with a typical

Parametric factor	Value	Context	Population	Reference
C_e (Equation 1)	$4.3.10^{-3}$	Weathered granite of Burkina Faso	6	Vouillamoz et al., 2005
	$2.4.10^{-4}$	Clayey-sands in Myanmar	7	Vouillamoz et al., 2007
C_y (Equation 2)	$2.8.10^{-1}$	Weathered granite of Burkina Faso	6	Vouillamoz et al., 2005
C_T (Equation 3)	$1.65.10^{-10}$	Sands, clay and limestone in France	3	Legchenko et al., 2002
	$4.9\ 10^{-9}$	Sands in France	11	Vouillamoz, 2003
	$6.7\ 10^{-9}$	Clayey-sands in Myanmar	14	Vouillamoz et al., 2007
	$1.7\ 10^{-8}$	Sands in Niger	7	Vouillamoz et al., in press
	$8.2\ 10^{-10}$	Weathered granite of Burkina Faso	13	Vouillamoz et al., 2005
	$3.5\ 10^{-8}$	Chalk in France	6	Vouillamoz, 2003
	$2.54\ 10^{-8}$	Clayey sands in Spain	3	Plata and Rubio, 2006
	$9.5\ 10^{-8}$	Clayey gravels in Spain	4	Plata and Rubio, 2006
	$8.67\ 10^{-7}$	Gravels and limestone in Spain	2	Plata and Rubio, 2006
C_T (Equation 4)	$2.8\ 10^{-12}$	Sands, clay and limestone in France	3	Legchenko et al., 2002
	$1.6\ 10^{-6}$	Clayey-sands in Cambodia	6	Vouillamoz et al., 2002
	$8.3\ 10^{-11}$	Fractured diorite	4	Legchenko et al., 2002
	$6.2\ 10^{-13}$	Fractured gneiss	4	Legchenko et al., 2002

Table 1. Selected parametric factors of conversion equations (uncorrected from temperature effects, Vouillamoz *et al.,* in press). Population is the number of soundings used to calculate the parametric factor
Tabla 1. Selección de valores para las constantes de calibración (sin la corrección por el efecto de la temperatura, Vouillamoz et al., *en prensa). La población se refiere al número de SRM utilizados para calcular la constante*

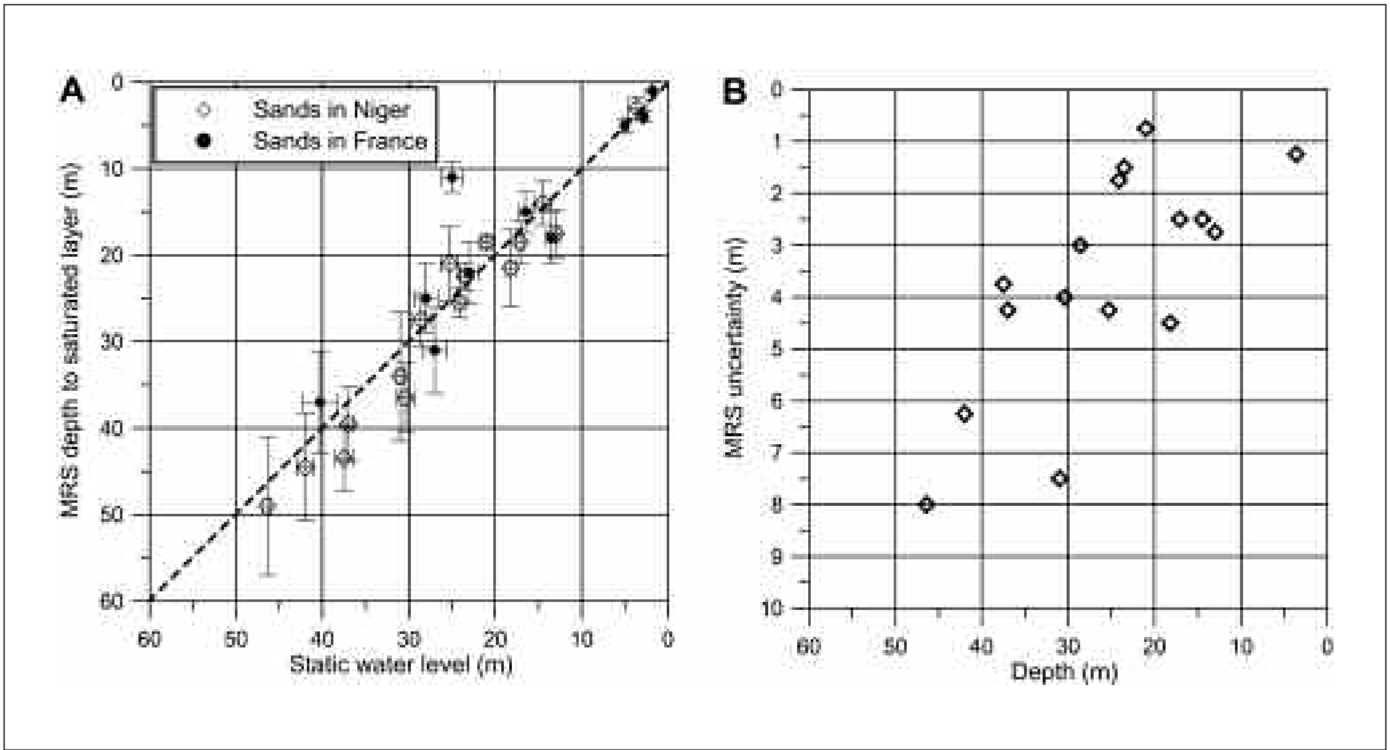

Fig. 1. MRS estimation of static water level (Vouillamoz, 2003; Vouillamoz *et al.,* in press). A: example of sands in Niger and France. B: uncertainty of MRS estimation versus depth for sands in Niger
Fig. 1. Estimación del nivel estático del agua mediante SRM (Vouillamoz, 2003; Vouillamoz et al.*, en prensa). A: ejemplo en arenas de Niger y Francia. B: incertidumbre de la estimación mediante SRM, en función de la profundidad de las arenas en Niger*

square shape loop of 75 to 150 meters side length, Vouillamoz (2003) found that the difference between aquifer bottom as obtained from boreholes and from MRS was on average -23%< *d* < +32% (population of 9) for depths ranging in-between 19 to 83 meters. The uncertainty of saturated thickness obtained from MRS is high as soon as the bottom of the saturated layer is below the half of the MRS loop size (Legchenko *et al.,* 1997). However, prior information and adapted inversion scheme (e.g. block inversion) reduce the uncertainty of MRS characterization (Vouillamoz *et al.,* in press).

As compared to mono-layer aquifers, multi-layer systems are not always well resolved because of the MRS loss of resolution with depth and because of the non-uniqueness of the geophysical interpretation. Figure 2 is an example of multi-layer aquifer of tertiary sediments (Paris sedimentary basin, France) that is identified as a heterogeneous mono-layer system by MRS. A square loop of 75 meters side was used at this site, and the thin clayey layer 40 meters deep in-between the two reservoirs is not well defined as it is situated below the half of the loop size. Moreover, the non-uniqueness of the geophysical interpretation (named the equivalence) makes the mono-layer solution acceptable to fit the observed data. The equivalence concerns mainly the product "water content times saturated thickness" ($\theta_{MRS}\,\Delta z$): a saturated layer of 10 meters thick and 10% of water content can not be accurately differentiated from a layer of 5 meters thick and 20% of water content if the middles of the layers are both located at the same depth (considering a reasonable measurement accuracy and below a certain depth). When interpreting the sounding, the range of equivalence on ($\theta_{MRS}\,\Delta z$) can be estimated using a variety of smoothing parameters in the MRS data inversion process (Vouillamoz, 2003; Rubio and Plata, 2005). Moreover, external information as borehole log or geophysical data reduce drastically the equivalence leading to an acceptable uncertainty on MRS parameters (Plata and Rubio, 2002; Vouillamoz, 2003; Vouillamoz *et al.,* in press).

Storativity and total porosity

Only few field experiments have been conducted to estimate storativity from MRS parameters. Both con-

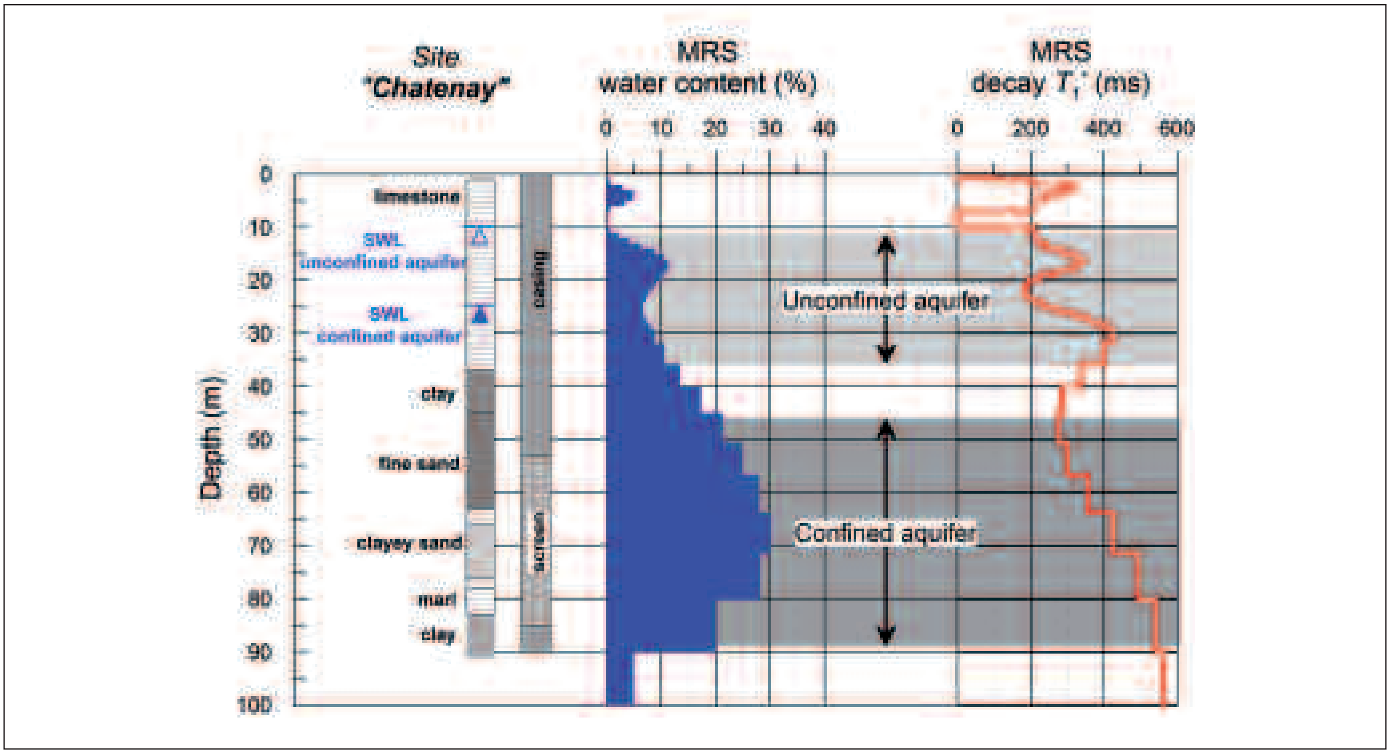

Fig. 2. Resolution of multi-layer aquifer (Vouillamoz, 2003)
Fig. 2. Resolución de un acuífero multi-capa (Vouillamoz, 2003)

version equations of elastic storativity (Equation 1) and specific yield (Equation 2) still need to be validated with more field experiments. Vouillamoz *et al.* (in press) compared the MRS water content to the total porosity calculated from the Bretjinski formula (De Marsily, 1986) using hydraulic conductivity obtained from pumping tests in southwest Niger (Figure 3A, population of 7). The MRS water content is 4% lower than the total porosity on average, what is acceptable for bound water in fine to medium grain size material (bound water is not measured by MRS but is part of the total porosity, see Lubczynski and Roy, 2007, this Issue). At the same locations, Vouillamoz *et al.* (in press) also compared MRS water content to specific yield estimated from a hydrogeological model computed at a regional scale (Massuel, 2005). They found that MRS water content was higher than the specific yield of 3.7% on average. Considering MRS water content of the saturated aquifer, MRS estimates the effective porosity rather than the specific yield (see Lubczynski and Roy, 2007, this Issue). The amount of water that is measured by MRS over the specific yield could be interpreted as capillary water of the de-saturated aquifer. However, the specific yield derived from the model can not be used to calibrate MRS water content as it is not a direct characterization of the aquifer. Other experiments revealed that the MRS water content can be less than the specific yield, what can be explained by the heterogeneity of the geomagnetic field that shortens the MRS signal (see section "Case histories in non-homogeneity magnetic Earth's field).

In confined aquifer of Myanmar, Vouillamoz *et al.* (2007) found that the elastic storativity estimate is slightly improved when using the developed form of Equation 1. The average difference with storativity calculated from pumping tests was -10%<d<+27% (Figure 3B, population of 7).

Transmissivity

The estimation of transmissivity from MRS using Equation 3 is reliable and has been validated in a variety of geological contexts (among others, Baltassat *et al.,* 2003; Vouillamoz, 2003; Plata and Rubio, 2006; Vouillamoz *et al.,* 2007). After temperature correction of both MRS water content and hydraulic conductivi-

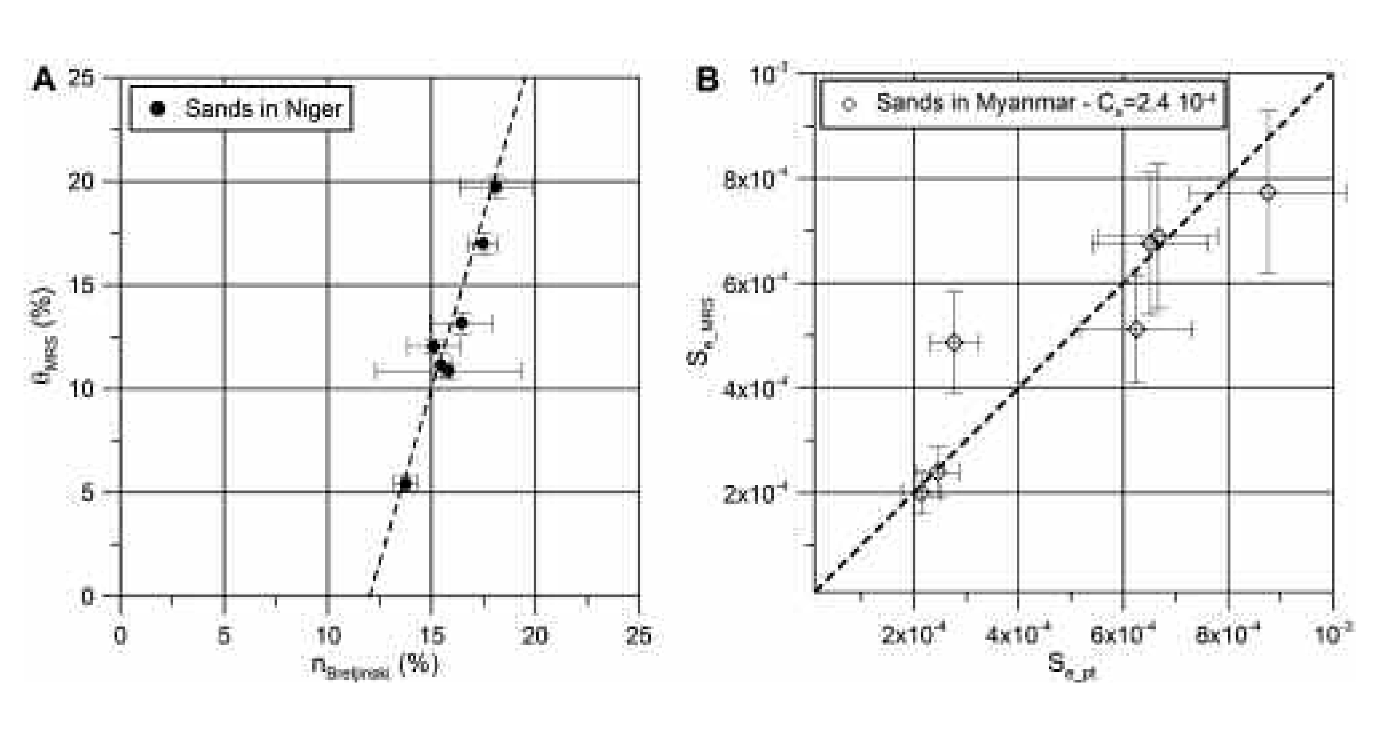

Fig. 3. MRS water content parameterization. A: total porosity of unconfined aquifer calculated from Bretjinski formula compared to MRS water content (Vouillamoz et al., in press). B: elastic storativity of confined aquifer calculated from pumping test compared to MRS elastic storativity calculated from Equation 1 (Vouillamoz et al., 2007). Ce=2.4 10^{-4}

Fig. 3. Evaluación de parámetros hidráulicos mediante SRM. A: porosidad total de un acuífero libre, calculada mediante la ecuación de Bretjinski, comparada con el contenido en agua deducido mediante SRM (Vouillamoz et al., en prensa). B: Coeficiente de almacenamiento elástico de un acuífero confinado calculado mediante ensayo de bombeo, comparado con el obtenido mediante SRM utilizando la Ecuación 1 (Vouillamoz et al., 2007). Ce=2.4 10^{-4}

ty of the *n* available data (Vouillamoz *et al.,* in press), the parametric factor C_T is calculated as

$$C_T = \sum_{i=1}^{n} T_{pt\_i} / \sum_{i=1}^{n} \theta_{MRS\_i} (T^*_{1\_i})^2 \Delta z_i$$

with T_{pt} the transmissivity calculated from pumping test interpretation (Figure 4A). Using the appropriate C_T value, the difference *d* between MRS and pumping test transmissivities is about -50%≤*d*≤ *+100%* (Figure 4B, population of 32) and is comparable to the average uncertainty on transmissivity estimated from pumping tests (Vouillamoz, 2003).

Field application

To locate the better site to drill boreholes in heterogeneous aquifer, Vouillamoz *et al.* (2002; 2007) showed that the use of MRS in the framework of a hydrogeological methodology improved the aquifer characterization and the drilling success rate. Furthermore, the total cost of drilling campaigns can be reduced because of the decrease of unsuccessful drillings. Figure 5 illustrates a methodology used in coastal clayey-sandy rocks of Myanmar (Vouillamoz *et al.,* 2007): (1) electrical resistivity measurements are conducted to check the resistivity contrasts over the targeted areas, (2) MRS are implemented on electrically resistive targets interpreted as possible sandy aquifers with fresh water, and (3) the aquifer storativity and transmissivity are calculated with conversion Equations 1 and 3, and the water salinity risk is estimated from the aquifer electrical resistivity.

The use of MRS to design hydrogeological model has been reported by several authors (Abraham *et al.,* 2003; Vouillamoz, 2003; Lubczynski and Gurwin, 2005; Girard *et al.,* 2006; Vouillamoz *et al.,* in press), but no work has yet been done to quantitatively evaluate the impact of MRS to groundwater modelling. Vouillamoz *et al.* (in press) compared the MRS characterization of a sandy aquifer in Niger with the output parameters

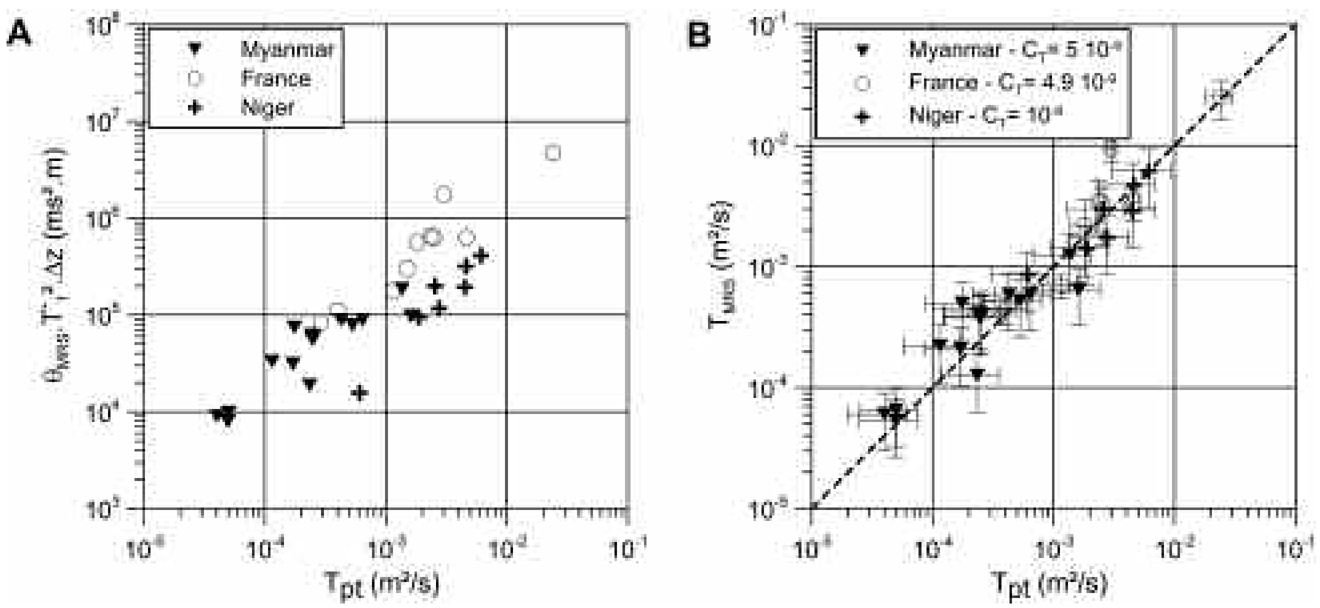

Fig. 4. MRS transmissivity parameterization (Vouillamoz, 2003; Vouillamoz *et al.,* 2007; Vouillamoz *et al.,* in press). A: comparison of MRS signal with pumping test transmissivity. B: MRS transmissivity calculated from Equation 3 (C_T corrected from temperature effects)
Fig. 4. Evaluación de la transmisividad mediante SRM (Vouillamoz, 2003; Vouillamoz et al., 2007; Vouillamoz et al., en prensa). A: comparación del factor de evaluación deducido mediante SRM con la transmisividad obtenida por ensayos de bombeo. B: Transmisividad calculada mediante la Ecuación 3 (C_T corregida de los efectos de temperatura)

of a hydrogeological model; they found that MRS is useful to better constrain the aquifer properties of the groundwater model thanks to rapid and dense sites network.

The global knowledge of an aquifer system can also be improved by the use of MRS. Girard *et al.* (2006) identified an unknown perched aquifer in a marl/limestone unit above a main sandy aquifer of France (Paris sedimentary basin). Vouillamoz *et al.* (in press) estimated the recharge of an unconfined aquifer in semi-arid Niger thanks to MRS water content. The joint use of TDEM and MRS has been often reported to successfully improve the aquifer characterization (Vouillamoz *et al.,* 2002; Dippel *et al.,* 2003; Goldman *et al.,* 1994; Chalikakis *et al.,* 2006). Moreover, the same Tx loop can be used for both TDEM and MRS, reducing the set up time of measurements (Vouillamoz *et al.,* 2002).

More experiments in the field of hydrogeology are presented in Lieblich *et al.* (1994), Plata and Rubio (1999), Yaramanci *et al.* (1999), Meju *et al.* (2002), Dippel *et al.* (2003), Plata *et al.* (2004), Lange *et al.* (2005b). Case histories in geotechnical and environmental projects have been also reported by Zhenyu Li (2003), Lange *et al.* (2005a) and Shushakov *et al.* (2003).

Finally, MRS is useful in non-consolidated sediments as it is the only available non-invasive method that can estimate the water presence, its distribution with depth, and after a calibration process the transmissivity of aquifer and probably soon its storativity. This information can be obtained by a few hours duration measurement, typically of 2 to 4 hours in common conditions. However, (1) MRS can not detect aquifer if the geomagnetic field is non-homogeneous as reported by Roy *et al.* (2006) and (2) highly electrical conductive layers reduce the investigation depth of MRS (Vouillamoz *et al.,* 2007). Apart from the loop size and the instrumentation power, electrical conductivity imposes a physical limitation to the investigation depth related to attenuation in ground of the electromagnetic field (Legchenko *et al.* 2006b). It is a serious limitation of the method in thick clayey layers or salty water areas where the penetration depth can be drastically reduced as illustrated in Myanmar (Figure 6). Deep aquifers that are in the "blind zone of MRS" (shadow zone of Figure 6) were not identified by the method. As overall result in Myanmar coastal area, 10 MRS were in blind zone over a total of 34. Moreover, ground resistivity has to be known in electrically conductive area to accurately interpret MRS (Legchenko *et al.* 2006b).

Case histories in hard-rocks basement

From the top to the bottom of a typical weathering profile in crystalline basement aquifer we find (1) the alterites that have usually low hydraulic conductivity but significant water-retention capacity, (2) the underlying weathered-fissured zone that has often both significant hydraulic conductivity and storativity properties, and (3) the fresh bedrock that has a very limited storativity and is highly permeable only locally where affected by fracturing (Figure 7).

Saturated reservoir geometry

When the 1D assumption is acceptable at the MRS scale (i.e. typically a volume defined by a surface area of 1.5 times the MRS loop size times a maximum depth corresponding to the loop size) the geometry of saturated alterites and weathered-fissured reservoirs is described by MRS with an acceptable accuracy. In the granitic rocks of Burkina Faso, Vouillamoz *et al.* (2005) found that the average difference between boreholes data and MRS inversion was 12% for the depth to the top of the unconfined saturated reservoir and 17% for the depth to the bedrock (population of 11).

In the same geological context of Burkina Faso, the average water content was higher and the average T_1^* was shorter for alterites than for the fissured-weathered reservoirs. This result is in accordance with the hydrogeological conceptual model of thick weathered zone where the storativity is higher and the hydraulic conductivity is less for the alterites than for the fissured zones (Figure 8).

In highly heterogeneous gneissic rocks of south-

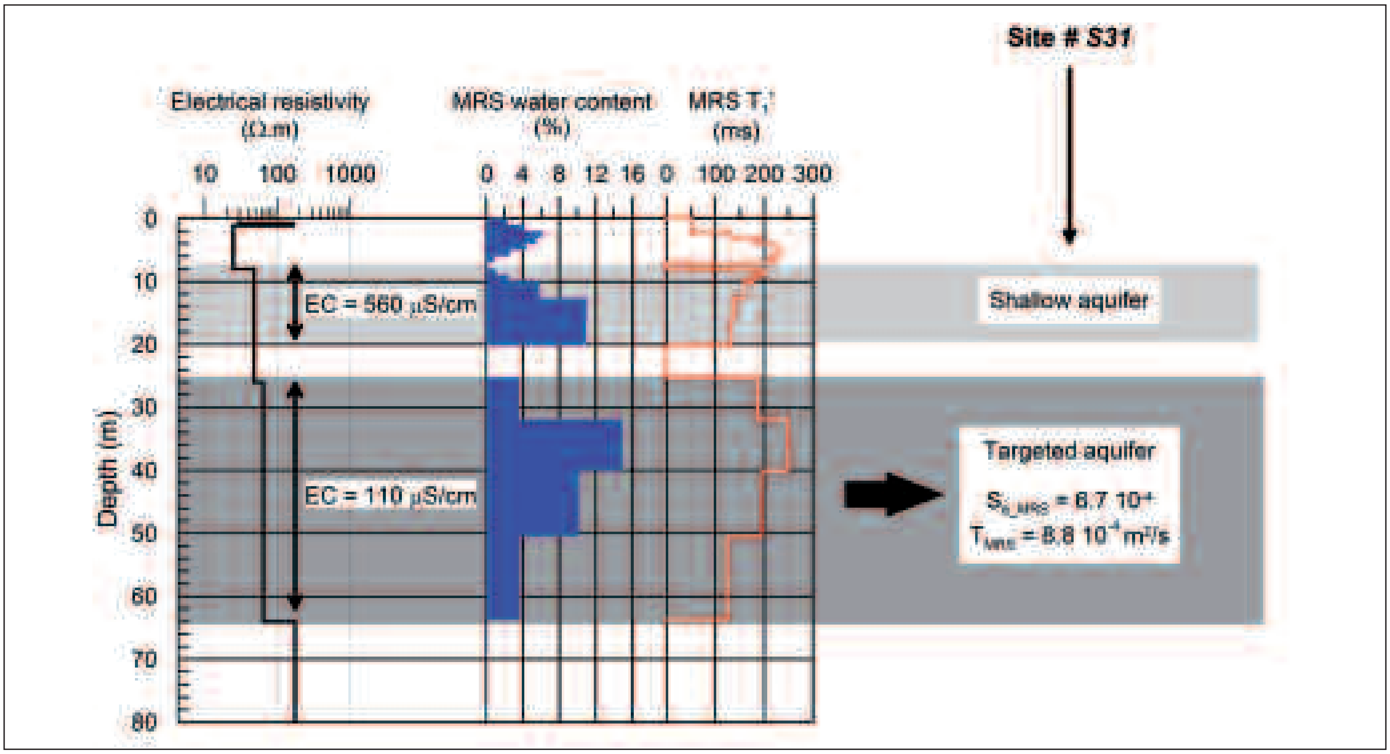

Fig. 5. Example of aquifer identification and characterization using complementary tools (Vouillamoz *et al.,* 2007). EC is the water electrical conductivity as estimated from electrical soundings. The deeper aquifer (from 25 to 65 meters) was targeted by drilling

Fig. 5. Ejemplo de identificación y caracterización de un acuífero empleando métodos complementarios (Vouillamoz et al., *2007). EC es la conductividad eléctrica del agua deducida mediante sondeos eléctricos. El acuífero más profundo (desde los 25 hasta los 65 metros) se verificó mediante un sondeo mecánico*

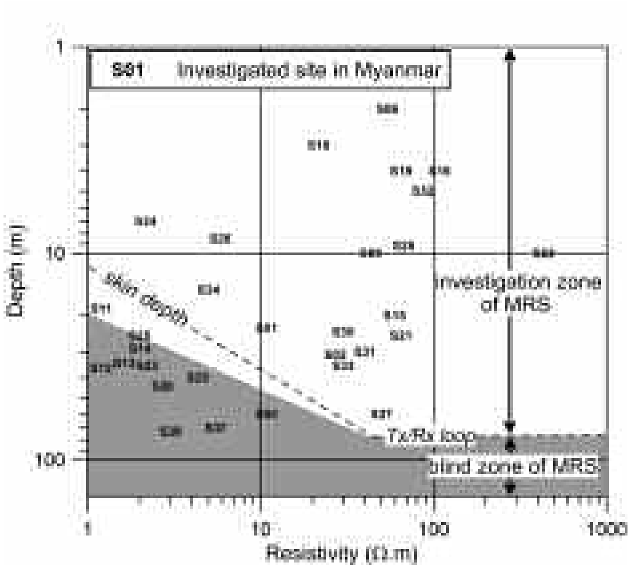

Fig. 6. Maximum depth of penetration of MRS according to the electrical resistivity of rocks, and limited to the MRS loop size (Vouillamoz *et al.,* 2007)
Fig. 6. Máxima penetración de los SRM en función de la resistividad eléctrica de las rocas, y su limitación debida a las dimensiones de la antena del SRM (Vouillamoz et al., *2007)*

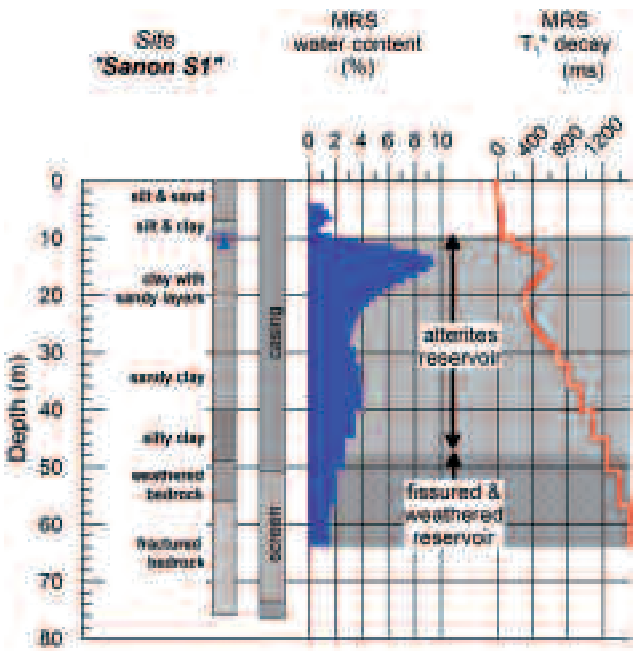

Fig. 8. MRS parameters in granite weathering profile of Burkina Faso (Vouillamoz *et al.,* 2005)
Fig. 8. Parámetros obtenidos mediante SRM sobre granito meteorizado en Burkina Faso (Vouillamoz et al., *2005)*

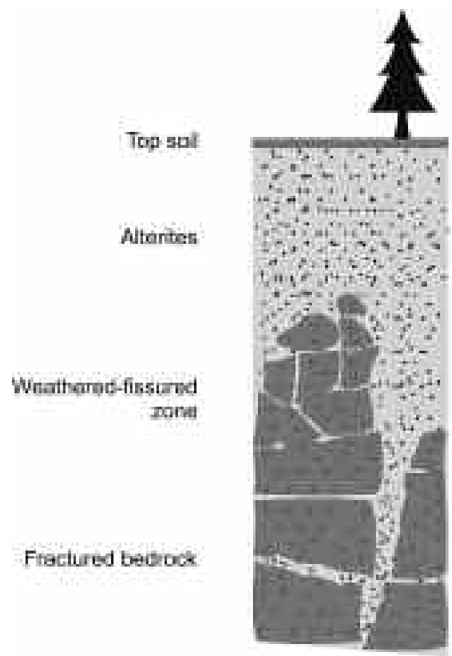

Fig. 7. Conceptual weathering profile of crystalline basement
Fig. 7. Modelo conceptual de la zona meteorizada de un basamento cristalino

ern India, Legchenko *et al.* (2006a) found that the reservoir geometry can be described in 2D using the available 1D apparatus if the size of the 2D structure is greater than the half of MRS loop (Figure 9).

The experiments in the use of MRS in hard-rocks aquifers indicate that the saturated fractures in bedrock cannot be identified with the current equipment because (1) water content less than about 1% and located below a depth of half the MRS loop size creates a too low signal to be measured (Vouillamoz *et al.,* 2005), and (2) the saturated alterites may screen MRS signal from deeper water-saturated fractures (Legchenko *et al.,* 2006a). This screening effect consists of reducing the interpreted MRS water content of a deep reservoir when it is topped by a shallower one of higher water content, what is quite common in bedrock aquifers. Calculations done by Baltassat *et al.* (2006) for granites of south India showed that the fissured reservoir is almost completely screened (and then undetectable) by the alterites reservoir when (1) the depth of the fissured zone is more than twice the depth of SWL in the alterites, and (2) the volume of

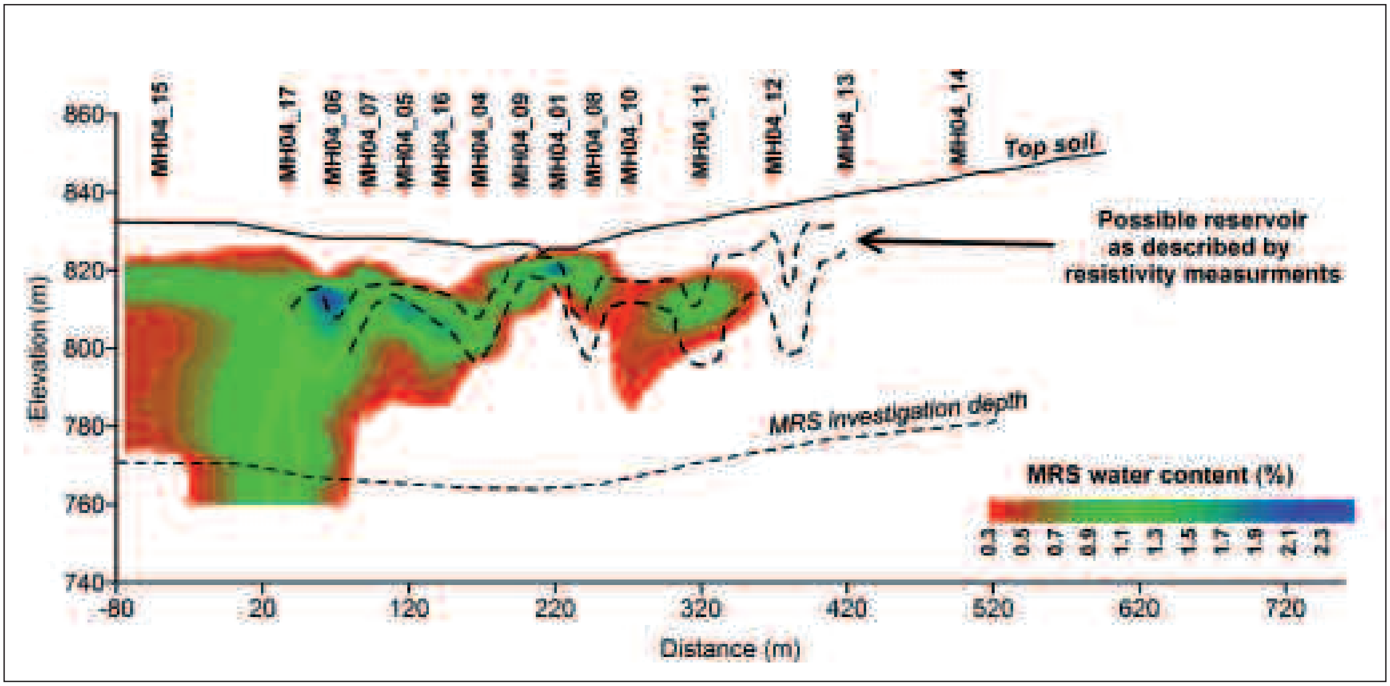

Fig. 9. Aquifer geometry derived from 1D MRS in gneiss rocks (Legchenko *et al.,* 2006a). MHXX_XX are the centres of MRS loops of 50 metres side length. The dashed lines represent the possible reservoir geometry as derived from 2D electrical measurements
Fig. 9. Geometría de un acuífero en gneis, obtenida mediante SRM en 1D (Legchenko et al., *2006a). MHXX_XX indica el centro de cada antena cuadrada de 50 m de lado. Las líneas discontinuas representan la posible geometría del acuífero según mediciones eléctricas en 2D*

water in the alterites is more than twice the volume of water in the fissured zone. The use of the MRS signal phase in the interpretation process can significantly reduce this effect, but it can not be done with the actual commercial software. An example of combined screening and suppression effect in basement granites of Burkina Faso is shown Figure 10 (Vouillamoz *et al.,* 2005). The MRS measurement was carried out with a 125 meters side length square loop and the signal to noise ratio was 1.6. Water content and T_1^* values are consistent for the alterites and weathered-fissured units, but quite no signal is detected from below 40 meters deep. An electrical logging was conducted in the borehole that indicates water productive fractures in the bedrocks. These fractures were also identified while drilling, but they are not detected by MRS. Meyer *et al.,* (2006) found that the density of fissures/fractures can control the capability of MRS to detect groundwater in hard-rocks of South-Africa.

Storativity and transmissivity

No conversion equation has been clearly validated to link MRS water content and bedrock aquifer storativity (Vouillamoz, 2003). Only few field experiments were carried out probably because accurate estimation of storativity from pumping test experiment is only possible if two neighbour wells are available. Vouillamoz *et al.* (2005) also showed that field conditions can make the choice between conversion Equation 1 and 2 difficult because (1) the property of confined or unconfined is not always clear, and (2) confined aquifer sometimes becomes locally unconfined because of the pumping effect, what makes the storativity a combination of elastic storativity and specific drainage (see Lubczynski and Roy, 2007 (this Issue) and Lubczynski and Roy, 2005).

Transmissivity derived from MRS using Equation 3 was found to be well correlated with transmissivity estimated from pumping tests in Burkina Faso (Vouillamoz *et al.,* 2005). The mean difference *d* between MRS and pumping test transmissivity was -31%≤ *d* ≤ +56% (population of 12), what was also the range of uncertainties of both geophysical and hydrogeological parameters (Figure 11). This result was obtained in alterites and weathered-fissured zones of several tens of meters thick that exhibited a hydraulic behaviour quite similar to a clayey-sandy medium at

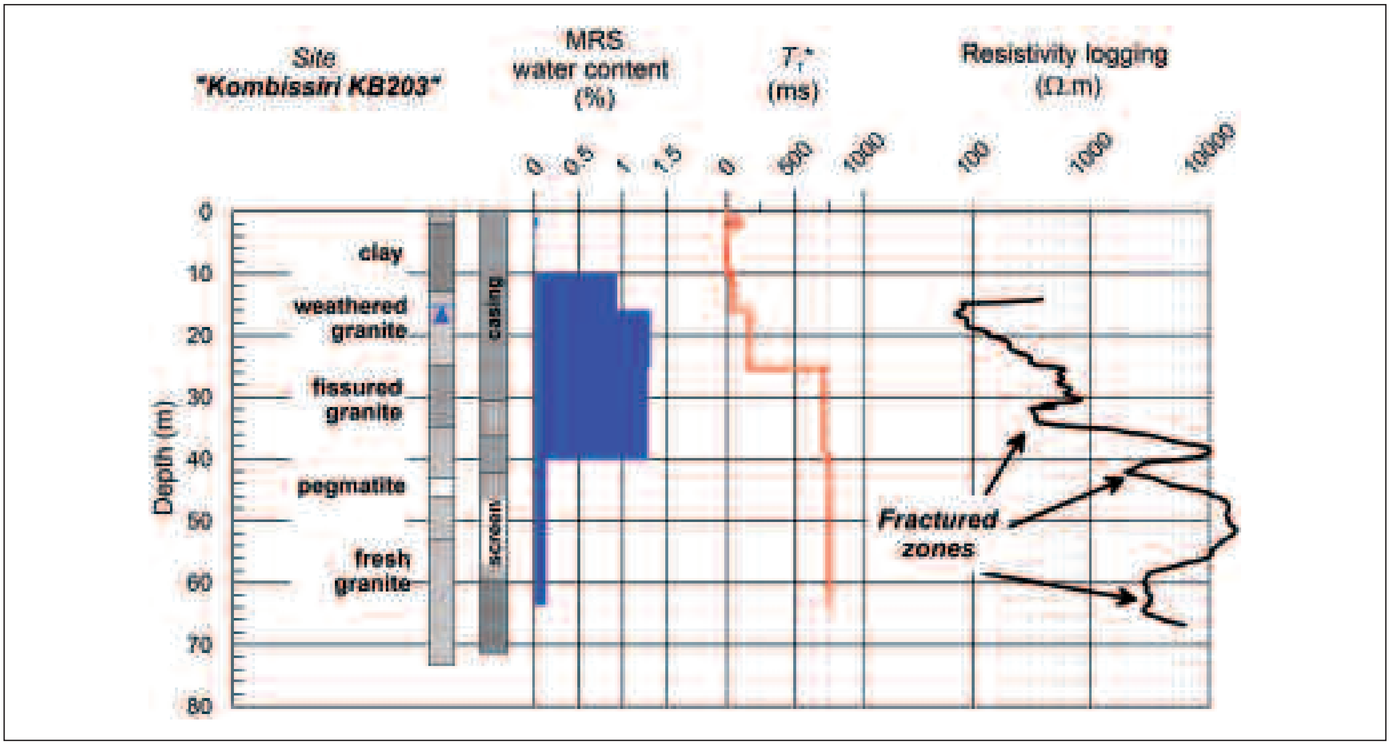

Fig. 10. MRS limitation for fractures localization: the deeper fractured zone identified by borehole logging is not identified by the MRS (Vouillamoz *et al.,* 2005)

Fig. 10. Limitación del SRM para localizar fracturas: la zona fracturada más profunda, identificada en el sondeo mecánico, no se identifica en el SRM (Vouillamoz et al., *2005)*

MRS and pumping test scale. No well documented field test has yet been carried out to estimate transmissivity of 2/3D structures in fractured rocks.

Field application

To implement productive boreholes in bedrock areas, hydrogeologists mainly target thickest zone of non-clayey alterites, well-developed fissured zones and productive deep fractures. Field experiences clearly reveal that the joint use of electrical resistivity measurements with MRS significantly facilitates the localization and the characterization of weathered and fissured targets (Figures 9 and 12). MRS must be integrated in the framework of a hydrogeological strategy: it comes at the end of the procedure to characterize targets that have been already identified by hydrogeological analysis, and usually confirmed with 1D or 2D electrical resistivity measurements (Delaporte *et al.,* 2003; Legchenko *et al.,* 2004; Vouillamoz *et al.,* 2005). Moreover, Vouillamoz *et al.* (2005) estimated that the joint use of MRS and 2D resistivity measurements can reasonably improve the borehole drilling success rate by 10 to 20% in Burkina Faso, and then saves money on the drilling program as soon as the common drilling success rate is low.

The knowledge of groundwater recharge and reserve is often a challenge to both develop and manage groundwater in basement areas. Descloitres *et al.* (2006) localized temporary recharge of a gneissic aquifer thanks to the joint use of MRS and electrical resistivity imagery in South India. Wyns *et al.* (2004) used jointly MRS water content with geometrical aquifer modelling to map successfully the groundwater reserve over a surface area of 270 km^2 of granite-gneiss reservoirs in France. They found that 80% of the reserves were stored in the weathered-fissured zone while the remaining 20% were in the alterites. The total volume of the groundwater reserve down to 50 to 70 meters deep was estimated to be about 3 years of common rainwater infiltration.

Hydrogeological modelling is a key tool for hydrogeologists who need a better understanding and a simulation of the behaviour of an aquifer system. Chaudhuri *et al.* (2005) used joint 2D electrical measurements and MRS characterization to run a stochastic model that simulates the geometry of a gneissic

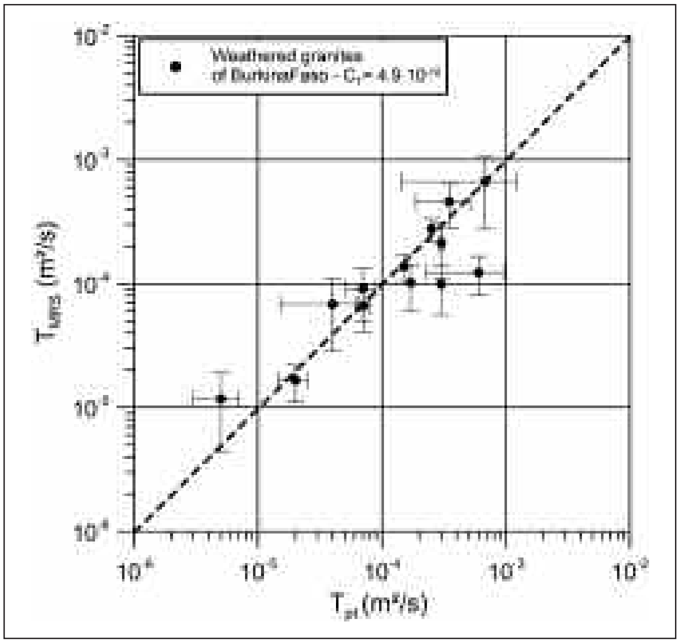

Fig. 11. MRS transmissivity calculated with Equation 3 versus aquifer transmissivity estimated from pumping tests in Burkina Faso (C_T corrected from temperature effects, modified from Vouillamoz *et al.,* 2005)
Fig. 11. Transmisividad obtenida mediante los datos de SRM (calculada mediante la Ecuación 3), frente a la transmivisivdad estimada mediante ensayos de bombeo, en Burkina Faso (C_T corregida de los efectos de temperatura, modificada de Vouillamoz et al., *2005)*

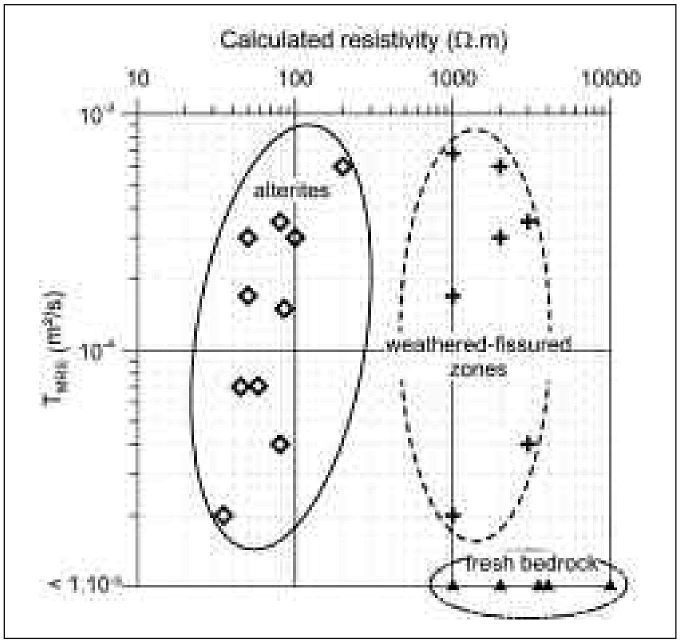

Fig. 12. Cross-characterization of granitic reservoirs of Burkina Faso using MRS transmissivity and electrical resistivity calculated from Schlumberger soundings (Vouillamoz *et al.,* 2005)
Fig. 12. Caracterización de acuíferos graníticos en Burkina Faso mediante la relación entre la transmisividad deducida por SRM y la resistividad eléctrica obtenida por sondeos Schlumberger (Vouillamoz et al., *2005)*

reservoir in south India. Other field experiments can be found in Portselan and Treshchenkov (2002), Krishnamurthy *et al.* (2003), Yuling *et al.* (2003), Baltassat *et al.* (2005).

Finally, MRS is currently useful in bedrock contexts to estimate the groundwater reserve in saturated alterites and weathered-fissured zones for resource management and modelling purpose, and to better locate borehole drilling sites mainly when high yield is targeted. However, MRS needs to be used with complementary methods in the framework of a hydrogeological survey to overcome its main limitations that are (1) its inefficiency to characterize fractures in the fresh rock, (2) its integrative characteristic that averages the measured parameters within the investigated volume (but it can also be an advantage to characterize properties of aquifer over a convenient scale for hydrogeology modelling), and (3) the measurement duration when low signal to noise ratio is encountered (a sounding can last as long as 20 hours in these environments, Vouillamoz *et al.,* 2005).

Case histories in carbonate rocks

Chalk and limestone rocks can exhibit various characteristics. At the scale of a MRS, the hydraulic behaviour of carbonate rocks could range from interstitial porosity medium as chalk or highly fissured limestone, to fracture porosity medium as fractured and karstified limestone.

Considering the rock matrix, chalk can have a high total porosity (up to 50%) but low storativity and hydraulic conductivity because of the very small size of the pores. Limestone rocks usually have a low total porosity of few percents and are not hydraulically conductive. However, the fissures and fractures, the joints and the dissolution structures of both chalk and limestone rocks can be highly permeable and porous.

Chalk rocks and densely fissured limestone

Because the amount of capillary water in unsaturated carbonates can be high and because the magnetic properties of the rocks are usually homogeneous, it is quite common to measure high MRS signal in the unsaturated zone (Miehé *et al.,* 2003). Boucher *et al.* (2006a) measured about 10% of water content in unsaturated chalk in Paris sedimentary basin (France) while the water content of the saturated zone was about 20%. Legchenko *et al.* (2002) also measured MRS signal in unsaturated limestone in Cyprus. This detection of water in the unsaturated zone makes MRS a promising tool to characterize chalk. A link between MRS decay constant and negative pressure of the unsaturated zone is under investigation (Boucher *et al.,* 2006a) and research activity is currently running on chalk characterization. However, a high amount of capillary water makes the contrast between MRS signal of unsaturated and saturated zone not always sufficient to estimate the geometry of saturated aquifers. A method based on an empirical link between static water level measured in wells and depth of the layer that exhibits the higher MRS water content was proposed by Girard *at al.* (2006).

Engineering works have been done in densely fissured limestone in France by the BRGM. The saturated limestone exhibited average water content of about 10%, and the hydraulic behaviour of the rocks was similar to an interstitial porous rock at the scale of the MRS. However, the estimation of the transmissivity from MRS signal (Equation 3) was not validated with a sufficient data set.

Other field experiments in carbonates rocks have been conducted by Gev *et al.,* 1996; Meju *et al.,* 2002; Abraham *et al.,* 2003; Boucher *et al.* 2003; Delaporte *et al.* 2003; among others.

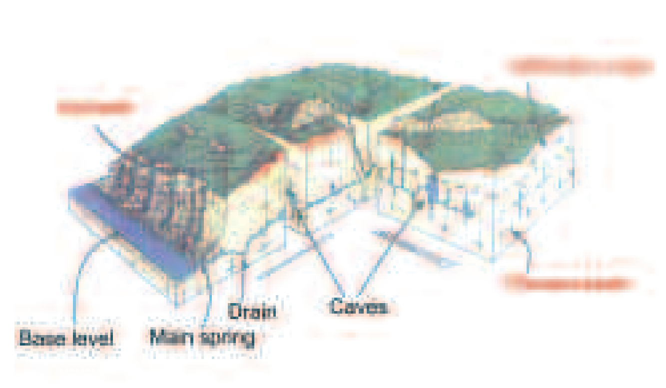

Fig. 13. Conceptual model of karstic system
Fig. 13. Modelo conceptual de un karst

Saturated karst geometry

The usual conceptual model of karstic system describes from the top to the bottom (1) the epikarst that is highly fissured and fractured, (2) the infiltration zone that can be up to several hundreds meters thick, and (3) the flooded karst (Figure 13). Both flooded karst and infiltration zones can store large amount of water in drains and caves but also in the limestone matrix, and the epikarst can sometimes bear water.

Few experiments have been conducted to check the capability of MRS to locate and characterize saturated karstic structures (Vouillamoz *et al.,* 2003; Boucher *et al.,* 2006b, Girard *et al.,* 2007). MRS's were implemented along a profile that crosses a known saturated cave or drain. A profile of 1D MRS can reveal with an acceptable accuracy the location of groundwater if the loop size and the distance between soundings are appropriate to the target, e.g. a loop size of about the maximum depth targeted and spacing between soundings of about the half loop size. When targets are of small size as compared to the loop size, the spacing between soundings has to be reduced to 5 or 10 meters and a real 2D inversion has to be used to obtain an accurate image (Boucher *et al.,* 2006b).

An example of limestone characterization is given by Vouillamoz *et al.* (2003) who investigated a karstic drain in southern France. They used a normalized hydraulic conductivity and transmissivity calculated from Equation 3 to successfully locate the saturated drain (Figure 14 A and B). Moreover, saturated epikarst and drain were differentiated because they exhibit a large difference in both water content and T_1^* values (Figure 14B).

Field application

Nowadays, MRS is useful in carbonate rocks that exhibit behaviour close to non-consolidated medium at the MRS scale thanks to high matrix interstitial porosity (mainly chalk) or dense fissures-fractures networks (both chalk and limestone). However the MRS characterisation is mainly qualitative because (1) the geometry of saturated reservoir is not easily accessible from MRS signal if the contrast of water content and decay constant between unsaturated and saturated zones is low, (2) the quantification of storativity from MRS water content has not yet been achieved, and (3) the quantification of transmissivity using Equation 3 has not yet been validated with sufficient experiments.

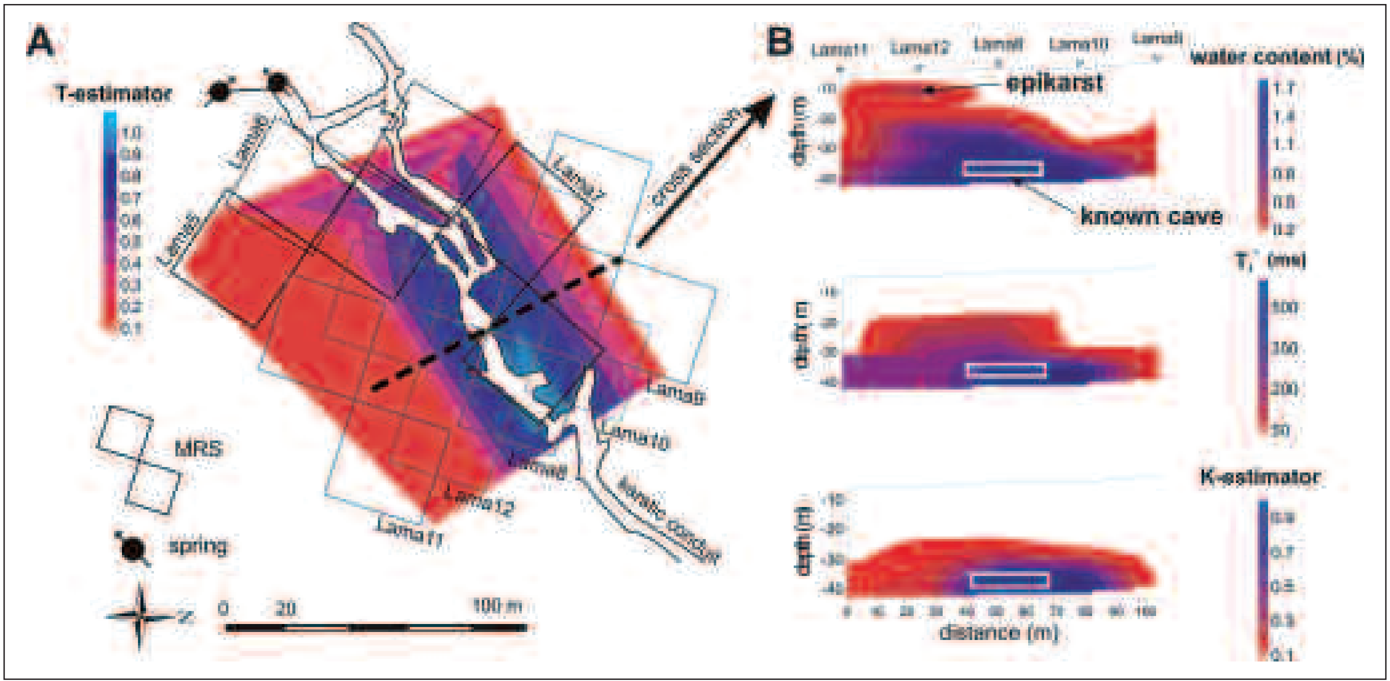

Fig. 14. Example of MRS application to locate a saturated karst (Vouillamoz *et al.,* 2003). A: location of drain using the normalized transmissivity (T-estimator) – B: cross section using 1D profiling to locate the saturated drain (below Lama8 sounding) and the epikarst (below Lama12 sounding)

Fig. 14. Ejemplo de aplicación de SRM para localización de un karst saturado (Vouillamoz et al., *2003). A: Localización utilizando la transmisividad normalizada (estimador T). B: cortes utilizando modelos 1D para localizar la zona saturada (bajo el SRM Lama8) y la zona de epikarst (bajo el SRM Lama12)*

In karsts, surveys are not widely performed because MRS signals generated by both saturated karst structures and limestone matrix are usually very low, what makes the measurements vulnerable to noise. Vouillamoz *et al.* (2003) computed the minimum volume of water that could be detected with the actual instrumentation according to the depth (Figure 15). They found that the amount of water has to be large enough and has to be shallow to complete a successful survey. Moreover, a large number of soundings has to be implemented to locate saturated karstic structures, what is time consuming as each sounding could last long (up to 20 hours in low signal to noise ratio).

Case histories in non-homogeneous magnetic Earth's field

MRS interpretation is not reliable or MRS measurement impossible when magnetic property of rocks makes the geomagnetic field non-homogeneous. Hydrogen nuclei that are not submitted to the same static field exhibit different Larmor frequency resulting in a macroscopic MRS signal diminished, below the instrumental threshold or inexistent (Legchenko *et al.,* 2002). It is both an instrumental and a methodological limitation since specific measurement procedure as the "Spin Echo" could be setup with lab devices.

It is not easy to assess on the field the heterogeneity of the geomagnetic field at the pore scale, because heterogeneity is not always linked to the value of rock magnetic properties. For instance, successful MRS has been carried out in South Africa and Botswana over rocks that exhibited high magnetic susceptibility values (about 10^{-2} SI). However, simple field measurements can help to estimate the risk of perturbation of MRS by the magnetic property of rocks (Vouillamoz, 2003). The risk is high if (1) the magnetic susceptibility of outcrops is heterogeneous and higher than about 10^{-3} SI, and (2) the geomagnetic field exhibits variations of more than 50 nT over the MRS loop surface area and at different elevations. Finally, a MRS sounding of only few moments can be implemented to check the feasibility of the measure-

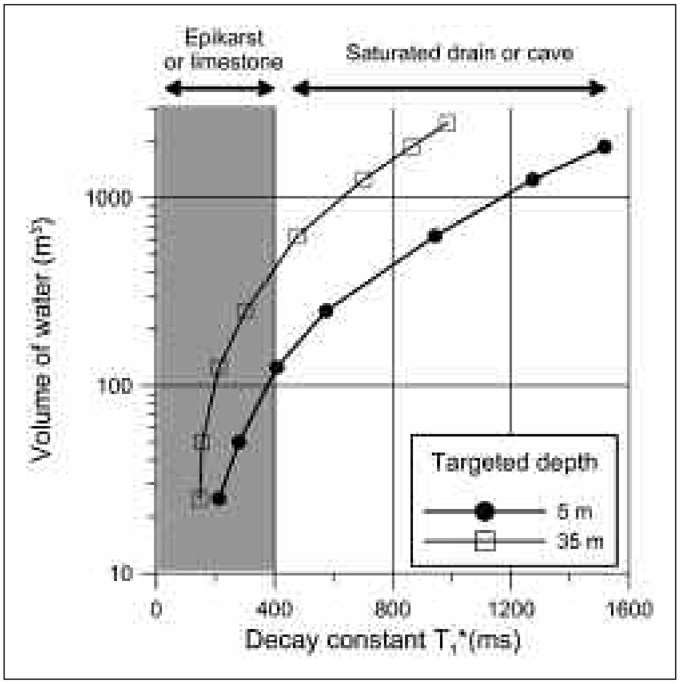

Fig.15. Capability of MRS to locate saturated karst structures (Vouillamoz *et al.,* 2003)
Fig. 15. Capacidad de los SRM para localización de estructuras kársticas saturadas (Vouillamoz et al., *2003)*

ment. MRS measurements in Earth's field non-homogeneity conditions have been reported in volcanic rocks (Vouillamoz, 2003), in sedimentary contexts (Legchenko *et al.,* 2002; Roy *et al.,* 2006) and in hard-rock basement (Baltassat *et al.,* 2006). Apart from extreme cases where MRS records are impossible, a major risk concerns medium heterogeneities of the geomagnetic field that make only part of the signal to be recorded. It can lead to erroneous MRS interpretation.

Field experiments in volcanic rocks

An example of undetectable aquifer is presented Figure 16 (Vouillamoz, 2003). It concerns volcanic rocks (ignimbrites) in Honduras where a MRS was implemented nearby a basaltic outcrop that was assessed with 2D resistivity imagery. The magnetic susceptibility of the basalt was 10^{-2} SI, and the geomagnetic field exhibited a large gradient over the MRS loop of about 5 Hz as expressed in Larmor frequency. Experimental MRS's were carried out with several Larmor frequencies but no MRS signal was recorded although the presence of a productive borehole.

Field experiments in sedimentary rocks

MRS experiments were conducted in south-east Canada by Roy *et al.* (2006), in non-consolidated sands, gravels and thin clay layers. The sites exhibited shallow SWL (few meters deep), high porosity (between 25 and 40%) and high hydraulic conductivity (10^{-5} to 10^{-3} m/s). Because no MRS signal was recorded, magnetic susceptibility was measured on outcropping sands and pebbles, and on borehole samples. A high contrast of magnetic susceptibility was found (from 0 up to 5.6 10^{-2} SI) and confirmed by the presence of fine-grained magnetite in the sediments. These magnetic grains produce at the pore level high gradient of magnetic field that was confirmed by laboratory measurements.

According to Roy *et al.* (2006) such geological context is widespread what makes a serious limitation of MRS use with the actual instrumentation and methodology.

Field experiments in weathered granite

Successful measurements are reported by Baltassat *et al.* (2006) in high gradient of magnetic susceptibility of weathered granite in India. They observed an increase with depth of the magnetic susceptibility (from 5 10^{-5} SI to 10^{-2} SI) that was explained by the weathering process of magnetite mineral to weakly magnetic minerals such as hematite. MRS was successfully implemented in this context and soundings produced different signals. Authors explained MRS signals with hydrogeological reasons (mainly variations of the water table) and not because of the variation of the rock magnetic properties.

Conclusion

Nowadays, MRS contribution to characterize aquifers in common conditions down to about 100 meters deep is highly valuable in rocks that exhibit behaviour of non-consolidated aquifer at the sounding scale (e.g. sediments, weathered and fissured hard-rocks, densely fissured or highly interstitial porous carbonates). In rocks that exhibit behaviour of fractured aquifer (e.g. low density fractured crystalline basements and limestone, karst) MRS is a useful complementary method but is not always effective for com-

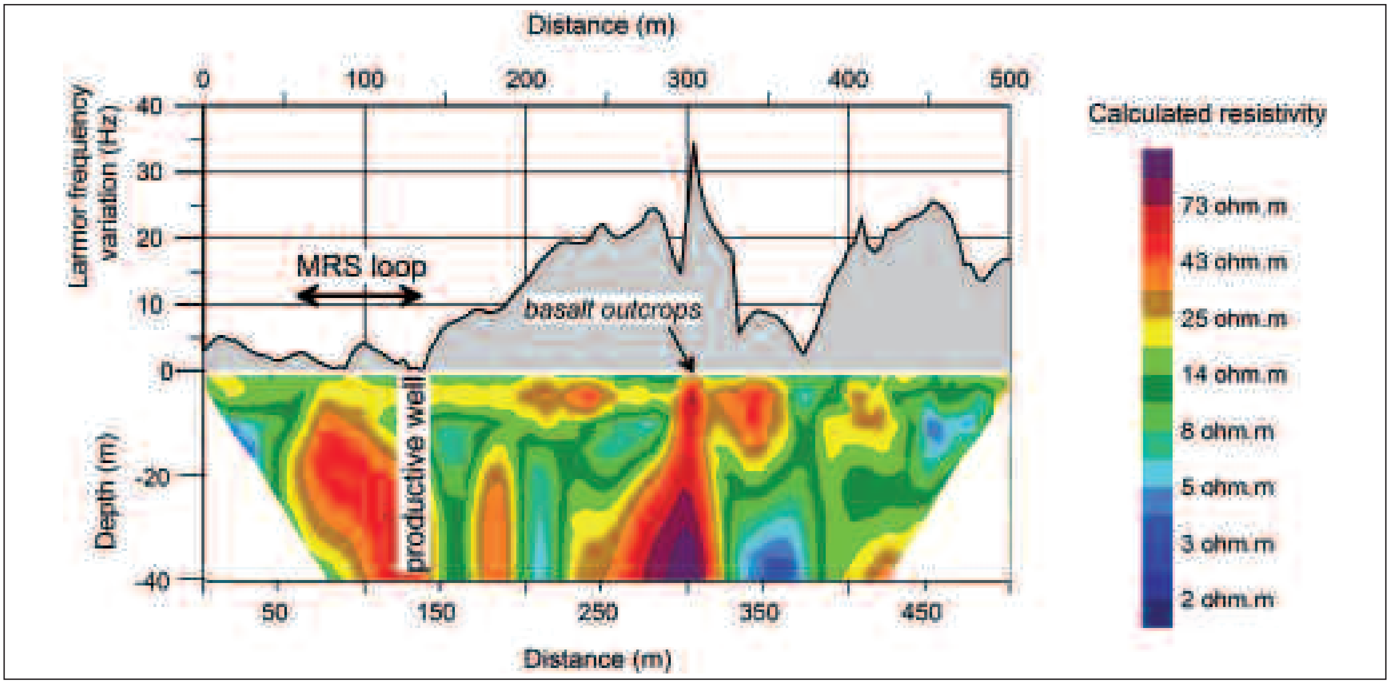

Fig.16. Example of magnetic properties of rocks that make the geomagnetic field heterogeneous and the MRS measurement impossible (Vouillamoz, 2003)

Fig. 16. Ejemplo de la imposibilidad de medición de SRM en el caso de rocas con propiedades magnéticas que dan lugar a un campo geomagnético heterogéneo (Vouillamoz, 2003)

mon engineering studies. In magnetic rocks MRS measurements are often impossible.

The main outputs of MRS concern the saturated aquifer geometry and transmissivity, and likely soon total porosity, effective porosity and storativity. (1) The geometry of aquifer can reasonably be estimated from MRS in 1D case. Interpolation in-between 1D soundings give accurate 2D geometry if the size of the MRS loop is smaller than about half the heterogeneity size. (2) The transmissivity calculated from MRS parameters has been validated in several contexts. It is estimated with an average difference as compared to pumping test transmissivity of $-50\% \leq d \leq +100\%$, what is also the average uncertainty on both hydrogeological and geophysical transmissivity estimations. (3) Links between MRS water content and total porosity and storativity have been observed, and conversion equations to estimate the specific yield and the elastic storativity from MRS have been proposed. However, these conversion equations are not yet validated with sufficient experiments. (4) The aquifer characterization is greatly improved when MRS is used in the framework of a hydrogeological methodology and jointly with complementary geophysical methods.

The main limitation encountered in the field with the actual instrumentation are (1) the need to parameterize the conversion equations between MRS output parameters and hydrogeological properties to obtain a quantitative interpretation of MRS, (2) electromagnetic noise that lowers the signal to noise ratio and makes urban areas but also low interstitial porosity and poorly fissured hard-rock aquifers difficult to survey, (3) the heterogeneity of magnetic properties of rocks that creates geomagnetic field gradient and makes MRS measurements impossible or interpretations wrong, and (4) the electrically conductive layers that reduce the investigation depth of MRS in salty water or clayey environments.

Further works and new developments will improve the MRS method for engineering purposes. (1) The instrumental development will reduce MRS vulnerability to electromagnetic noise. It will improve both the accuracy of measurement and the MRS capability to investigate new contexts as low porosity rocks. (2) The instrumental development will allow new protocols of measurement to be used on the field, as Spin Echo. It will be possible to use MRS in other geological formations such as volcanic rocks, and it will improve the reliability of interpretation in heterogeneous geomagnetic field conditions. (3) Conversion equations used to calculate hydrogeological properties of aquifers from MRS parameters will be validated and upgraded. A new conversion equation to estimate specific yield jointly from MRS water content and MRS decay constants will be proposed, leading a more reliable storativity estimate. New conversion equations will also be proposed using together MRS and complementary geophysical parameters as electrical resistivity. It will improve the global characterization of aquifers. (4) Convenient field methodology for 2D-3D imagery will be developed for improving the MRS resolution in highly heterogeneous media. (5) New instrumentation will be developed to characterize the unsaturated zone of aquifers.

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